

The Peak Structure in the In-Flight ${}^3\text{He}(K^-, \Lambda p)n$ Reaction Around the $\bar{K}NN$ Threshold

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We theoretically investigate the origin of the peak structure around the K^-pp threshold observed in the in-flight ${}^3\text{He}(K^-, \Lambda p)n$ reaction in the recent E15 experiment at J-PARC. For this purpose, we consider two scenarios to produce the peak. One is that the $\Lambda(1405)$ is generated but it does not correlate with p , and the uncorrelated $\Lambda(1405)p$ system subsequently decays into Λp . The other one is that the $\bar{K}NN$ bound state is indeed generated and decays into Λp . As a result, the experimental signal is qualitatively well reproduced in the $\bar{K}NN$ bound scenario, definitely discarding the uncorrelated $\Lambda(1405)p$ one.

KEYWORDS: kaonic nuclei, J-PARC E15 experiment, chiral dynamics

1. Introduction

Because the interaction between antikaon (\bar{K}) and nucleon (N) is strongly attractive [1, 2], we expect that there should exist bound states of \bar{K} and nuclei. They are referred to as kaonic nuclei. There are at least two motivations to study kaonic nuclei. One is that kaonic nuclei are exotic states of many-body systems tied by the strong interaction, which contain a hadron other than nucleons, and the other is that kaonic nuclei are a good “laboratory” to prove kaons in finite nuclear density. In particular, the simplest kaonic nucleus $\bar{K}NN(I = 1/2)$, sometimes called K^-pp , has been intensively studied in both theoretical [3–9] and experimental [10–14] sides (see also Ref. [15]). However, at present, there has been no consensus on the properties of the $\bar{K}NN$ bound state.

In this line, a very attractive result comes out from the recent J-PARC E15 experiment [16]. In this experiment, they observed a peak structure near the K^-pp threshold in the Λp invariant mass spectrum of the in-flight ${}^3\text{He}(K^-, \Lambda p)n$ reaction with a kaon momentum in the laboratory frame of $k_{\text{lab}} = 1 \text{ GeV}/c$. This peak can be described by the Breit-Wigner formula with mass $M_X = 2355^{+6}_{-8}(\text{stat.}) \pm 12(\text{sys.}) \text{ MeV}$ and width $\Gamma_X = 110^{+19}_{-17}(\text{stat.}) \pm 27(\text{sys.}) \text{ MeV}$ [16]. This could be a signal of the $\bar{K}NN(I = 1/2)$ bound state with a binding $\sim 15 \text{ MeV}$ from the K^-pp threshold.

In this study, our motivation is to investigate what is the origin of the peak structure observed in the J-PARC E15 experiment [16]. For this purpose we take into account two possible mechanisms for producing a peak in the mass spectrum. One is that the $\Lambda(1405)$ is generated but it does not correlate with the p , and the uncorrelated $\Lambda(1405)p$ system subsequently decays into Λp . This uncorrelated $\Lambda(1405)p$ system may create a peak even if they do not bind because the $\Lambda(1405)$ exists below the $\bar{K}N$ threshold. The other is that the $\bar{K}NN$ bound state is indeed generated and decays into Λp , which can create a peak in the Λp invariant mass spectrum if the signal is strong enough. In the following,

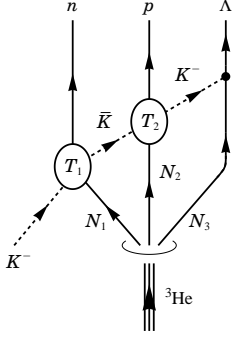


Fig. 1. Feynman diagram most relevant to the three-nucleon absorption of a K^- via an uncorrelated $\Lambda(1405)p$ system [17]. We take into account the antisymmetrization for the three nucleons in ^3He .

we concentrate on the $^3\text{He}(K^-, \Lambda p)n$ reaction with a kaon momentum in the laboratory frame of $k_{\text{lab}} = 1 \text{ GeV}/c$. The details of the calculations are given in Ref. [17].

2. Uncorrelated $\Lambda(1405)p$ scenario

First of all, we would like to consider the scenario of the uncorrelated $\Lambda(1405)$ and proton. For this scenario we employ the most relevant diagram shown in Fig. 1. The scattering amplitude of this reaction is fixed as follows. The ^3He wave function is obtained as an antisymmetrized system of three nucleons in a harmonic oscillator potential. The amplitudes of the first collision, $T_1(K^- n \rightarrow K^- n)$ and $T_1(K^- p \rightarrow \bar{K}^0 n)$, are taken from the differential cross sections of each reaction at $k_{\text{lab}} = 1 \text{ GeV}/c$. The amplitudes of the second collision, $T_2(K^- p \rightarrow K^- p)$ and $T_2(\bar{K}^0 n \rightarrow K^- p)$, are calculated in the chiral unitary approach [1, 2, 18, 19] and we effectively take into account the kaon absorption width in the kaon propagator. The $K^- p \Lambda$ vertex is fixed by chiral perturbation theory, and the intermediate kaon energy is determined in two options: the Watson approach (A) and truncated Faddeev approach (B) [20].

Now we can calculate the Λp invariant mass spectrum of the reaction $^3\text{He}(K^-, \Lambda p)n$ [17], which is shown in Fig. 2 together with the experimental (E15) data and its fit [16] in arbitrary units. As one can see, in both options A and B, the peak structure is inconsistent with the experimental data. Actually, while the peak appears at 2355 MeV in the experiment, we obtain the peak at more than 2370 MeV. In particular, we cannot reproduce the behavior of the lower tail $\sim 2.3 \text{ GeV}$. Therefore, the E15 signal in the $^3\text{He}(K^-, \Lambda p)n$ reaction is not the uncorrelated $\Lambda(1405)p$ state.

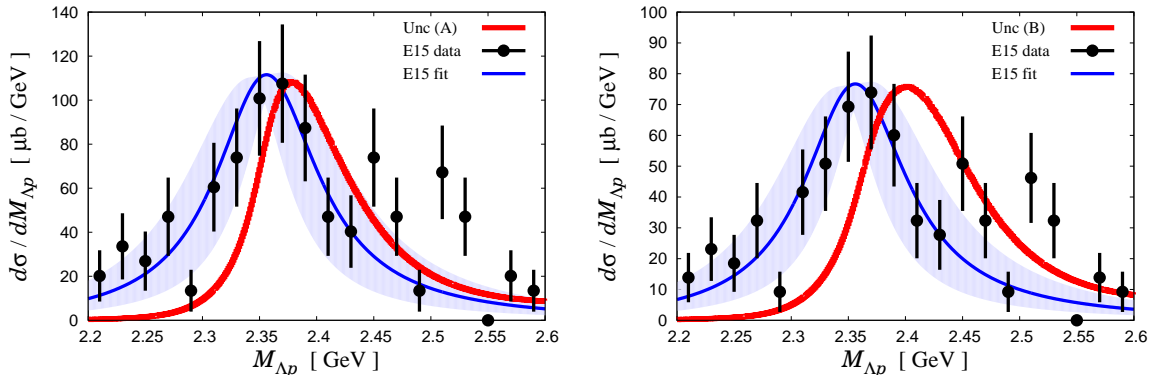


Fig. 2. Mass spectrum for the Λp invariant mass of the in-flight $^3\text{He}(K^-, \Lambda p)n$ reaction in the uncorrelated $\Lambda(1405)p$ scenario. Calculations are done in option A (left) and option B (right) [17]. The experimental (E15) data and its fit are taken from Ref. [16] and shown in arbitrary units.

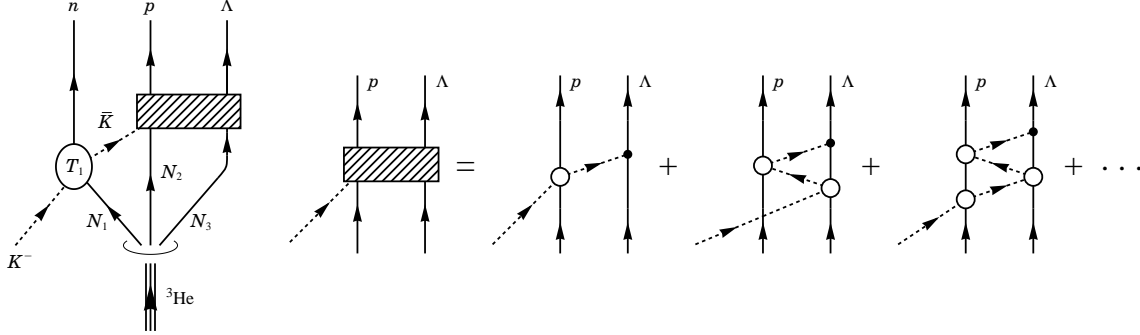


Fig. 3. Feynman diagram most relevant to the three-nucleon absorption of a K^- in the $\bar{K}NN$ bound scenario. The multiple kaon scattering between two nucleons is shown as the diagrammatic equation in right [17], where dashed lines and open circles represent the kaon and the $\bar{K}N \rightarrow \bar{K}N$ amplitude in the chiral unitary approach, respectively. We take into account the antisymmetrization for the three nucleons in ${}^3\text{He}$.

3. $\bar{K}NN$ bound scenario

Next we consider the $\bar{K}NN$ bound scenario. For this scenario we employ the most relevant diagram shown in Fig. 3. The scattering amplitude of this reaction is fixed as follows. We use the same ${}^3\text{He}$ wave function, amplitudes T_1 , intermediate kaon energy, and $\bar{K}N\Lambda$ vertex as in the uncorrelated $\Lambda(1405)p$ case. On the other hand, after the first collision of the kaon, we make the multiple scattering of the kaon with two nucleons, which is diagrammatically shown in the right part of Fig. 3. In this study we employ the fixed center approximation [8] to calculate this multiple scattering amplitude, where the kaon absorption width is effectively taken into account in the kaon propagator so as to reproduce the result of the width of the $\bar{K}NN$ bound state in Ref. [21]. In the present formulation and parameters, the multiple kaon scattering amplitudes in the fixed center approximation generate a peak at around 2350 MeV together with a resonance pole $2354 - 36i$ MeV.

Now let us calculate the Λp invariant mass spectrum in the $\bar{K}NN$ bound scenario. The result is shown in Fig. 4 together with the experimental (E15) data and its fit [16] in arbitrary units. An important finding is that our mass spectrum is consistent with the experimental one within the present error. In particular, we can reproduce the tail at the lower energy ~ 2.3 GeV. This implies that our spectrum supports the explanation that the E15 signal in the ${}^3\text{He}(K^-, \Lambda p)n$ reaction is indeed a signal

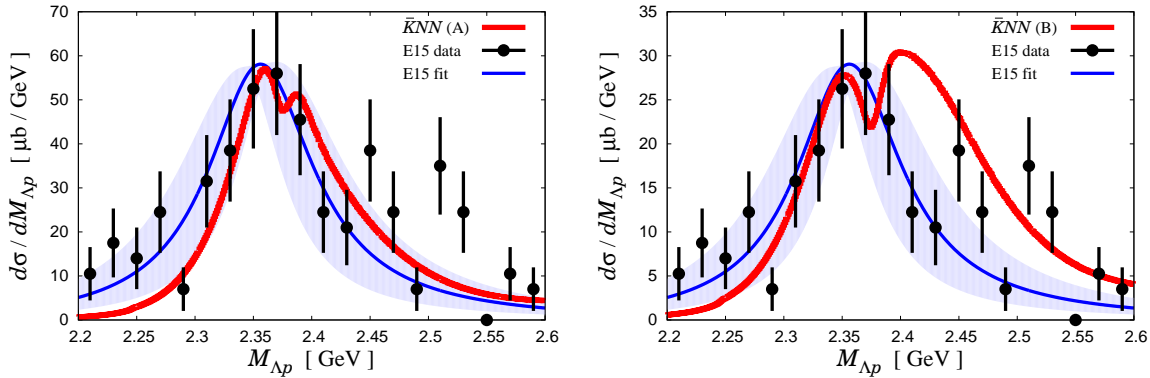


Fig. 4. The same as Fig. 2 but in the $\bar{K}NN$ bound scenario [17]. Calculations are done in option A (left) and option B (right).

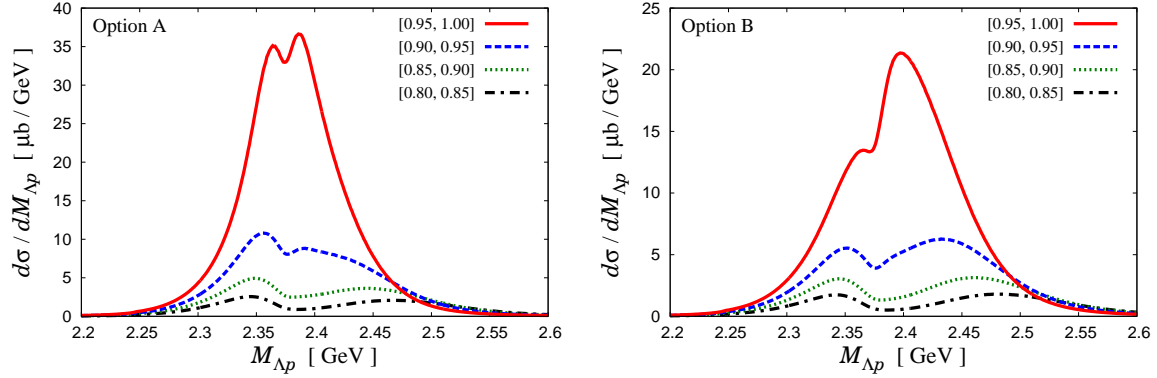


Fig. 5. Mass spectrum in the $\bar{K}NN$ bound scenario with the angular restriction $\cos \theta_n^{\text{cm}} \in [0.95, 1.00]$, $[0.90, 0.95]$, $[0.85, 0.90]$, and $[0.80, 0.85]$. Calculations are done in option A (left) and option B (right).

of the $\bar{K}NN$ bound state. In addition, we observe a two-peak structure below and above the $\bar{K}NN$ threshold. Actually, the lower peak is the signal of the $\bar{K}NN$ bound state, and the higher peak comes from the quasi-elastic kaon scattering in the first step, i.e., when the kaon after the collision T_1 goes almost on its mass shell. Here we also note that the total cross section becomes $7.6 \mu\text{b}$ ($5.6 \mu\text{b}$) in option A (B), which is qualitatively consistent with the empirical value $7 \pm 1 \mu\text{b}$ [16].

Finally, in Fig. 5 we show the mass spectrum with the restriction of the final-state neutron scattering angle: $\cos \theta_n^{\text{cm}} \in [0.95, 1.00]$, $[0.90, 0.95]$, $[0.85, 0.90]$, and $[0.80, 0.85]$. From the figure, one can see that the mass spectrum is dominant in the forward neutron scattering, $\cos \theta_n^{\text{cm}} = 1$, and is suppressed as the scattering angle θ_n^{cm} increases. Furthermore, we can observe how the two peaks move as the scattering angle θ_n^{cm} increases; the signal of the $\bar{K}NN$ bound state stays at ~ 2.35 GeV, but the peak of the quasi-elastic kaon scattering shifts upward due to its kinematics.

4. Summary and outlook

In this study we have investigated the origin of the peak structure near the $\bar{K}NN$ threshold in the $^3\text{He}(K^-, \Lambda p)n$ reaction observed in J-PARC E15 experiment. From the calculation of the Λp invariant mass spectrum, the experimental signal is qualitatively well reproduced in the scenario that the $\bar{K}NN$ bound state is indeed generated, and we can definitely discard the scenario that the $\Lambda(1405)$ is generated but does not correlate with the p .

The final goal of the present study is to prove that the E15 peak is indeed the $\bar{K}NN$ signal with the help of experimental studies. In order to achieve this, we need to check consistency between experiments and theories for various quantities. In this line, much is expected from the high statistics data that are coming from the second run of E15 [22]. With more data, we will be able to compare more things such as the angular dependence of the signal and the $\Lambda p/\Sigma^0 p$ branching ratio [23, 24].

References

- [1] N. Kaiser, P. B. Siegel and W. Weise: Nucl. Phys. A **594** (1995) 325.
- [2] E. Oset and A. Ramos: Nucl. Phys. A **635** (1998) 99.
- [3] Y. Akaishi and T. Yamazaki: Phys. Rev. C **65** (2002) 044005.
- [4] N. V. Shevchenko, A. Gal and J. Mares: Phys. Rev. Lett. **98** (2007) 082301.
- [5] Y. Ikeda and T. Sato: Phys. Rev. C **76** (2007) 035203.
- [6] A. Dote, T. Hyodo and W. Weise: Nucl. Phys. A **804** (2008) 197.
- [7] S. Wycech and A. M. Green: Phys. Rev. C **79** (2009) 014001.
- [8] M. Bayar, J. Yamagata-Sekihara and E. Oset: Phys. Rev. C **84** (2011) 015209.

- [9] N. Barnea, A. Gal and E. Z. Liverts: Phys. Lett. B **712** (2012) 132.
- [10] M. Agnello *et al.* [FINUDA Collaboration]: Phys. Rev. Lett. **94** (2005) 212303.
- [11] T. Yamazaki *et al.*: Phys. Rev. Lett. **104** (2010) 132502.
- [12] A. O. Tokiyasu *et al.* [LEPS Collaboration]: Phys. Lett. B **728** (2014) 616.
- [13] Y. Ichikawa *et al.*: PTEP **2015** (2015) 021D01.
- [14] T. Hashimoto *et al.* [J-PARC E15 Collaboration]: PTEP **2015** 061D01.
- [15] T. Nagae: Nucl. Phys. A **954** (2016) 94.
- [16] Y. Sada *et al.* [J-PARC E15 Collaboration]: PTEP **2016** (2016) 051D01.
- [17] T. Sekihara, E. Oset, and A. Ramos: PTEP **2016** (2016), in press [arXiv:1607.02058 [hep-ph]].
- [18] J. A. Oller and U. G. Meissner: Phys. Lett. B **500** (2001) 263.
- [19] D. Jido, J. A. Oller, E. Oset, A. Ramos and U. G. Meissner: Nucl. Phys. A **725** (2003) 181.
- [20] D. Jido, E. Oset and T. Sekihara: Eur. Phys. J. A **49** (2013) 95.
- [21] M. Bayar and E. Oset: Phys. Rev. C **88** (2013) 044003.
- [22] F. Sakuma *et al.*: talk in this conference; T. Yamaga *et al.*: talk in this conference.
- [23] T. Sekihara, D. Jido, and Y. Kanada-En'yo: Phys. Rev. C **79** (2009) 062201.
- [24] T. Sekihara, J. Yamagata-Sekihara, D. Jido, and Y. Kanada-En'yo: Phys. Rev. C **86** (2012) 065205.